Ballistic-electron-emission microscopy and spectroscopy of metal/GaN interfaces

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BEEM spectroscopy and imaging have been applied to the Au/GaN interface. In contrast to previous BEEM measurements, spectra yield a Schottky barrier height of 1.04 eV that agrees well with the highest values measured by conventional methods. A second threshold is observed in the spectra at about 0.2 V above the first threshold. Imaging of the Au/GaN interface reveals transmission in nearly all areas, although the magnitude is small and varies by an order of magnitude. BEEM of other GaN material shows no transmission in any areas.
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Interest in GaN as a promising material for light emitting devices and high-power amplifiers has grown quickly in recent years, due to its wide band-gap, high-temperature stability and chemical inertness. Unfortunately, growth of high-quality GaN has been hindered by lack of a suitable substrate, which causes difficulties in maintaining high crystal quality, and by high background doping levels. Electronic properties of interfaces to GaN and its alloys are still not well understood, and macroscopic electrical characterization is hindered by defects.

Ballistic-electron-emission microscopy [1] (BEEM) is a scanning tunneling microscopy [2] (STM) technique which was developed for the investigation of buried interfaces and hot-carrier transport. BEEM provides the high spatial resolution inherent in STM, allowing the characterization of specific interface areas only several square nm in size. In addition, interface properties may be directly imaged by scanning the STM tip. BEEM is sensitive to interface band structure [1], hot-carrier scattering [3], and the presence of interface defects [4].

The GaN layer used in this work was grown by MOCVD on a (0001) oriented sapphire substrate using TMG and ammonia as source materials and disilane to supply the donor dopant. Growth consisted of a low temperature nucleation layer followed by a higher temperature GaN layer. The GaN growth temperature was 1040° C as measured by optical pyrometer. The one-hour growth at a pressure of 150 T produced a GaN layer 2.2 microns thick. Room temperature carrier concentration, as determined by Hall measurement, was 1.2×10^{17} cm^{-3}, with a mobility of 534 cm^2/Vs. The measured FWHM of the (004) X-ray peak was 284 arc-seconds.

Wafers were diced into 4 mm squares and transferred into a nitrogen-purged glove-box for chemical cleaning. Ohmic contacts were formed to the GaN layer at the corner of the sample, either by application of molten In or by annealed Ti/Al pads. Both methods formed adequate ohmics for BEEM measurements. Samples were spin-etched using 1:10 HCl:ethanol and directly transferred into the load-lock attached to the evaporation chamber. Au was deposited at a pressure of 2×10^{-9} T. All samples discussed here used 6 nm Au layers. After Au deposition the samples were transferred to the STM, also located in a nitrogen glove-box. BEEM measurements were performed at room temperature. Further sample fabrication and measurement details have been presented elsewhere [5].

Our previous attempts to perform BEEM spectroscopy on metal/GaN structures using other GaN epilayers resulted in the absence of measurable collector current (down to the detection level of several fA), although low-leakage Schottky contacts could be fabricated on that material. Over 25 different samples were made under various preparation conditions, and using Au, Pd, and Pt as base metals. Various surface preparations were attempted, including hot aqua regia and HCl surface cleans, and the possibility of a defective surface layer was investigated by etching a fraction of the GaN away using hot KOH. None of these attempts produced measurable collector current, even at tunnel voltages as high as 3.5 V.

As will be discussed below, all BEEM samples fabricated on the newer material produced a measurable BEEM signal, although the magnitude was extremely small, even using thin (5 nm) Au base layers. Average observed collector current was on the order of 0.7 pA (for a 2 nA tunnel current and 1.6 V tunnel voltage), which is more than two orders of magnitude smaller than theory would predict. A tunnel current of 2 nA was used for BEEM spectroscopy and imaging in order to increase collector current.

Due to the extremely low level of BEEM current, many spectra were averaged together to increase signal-to-noise. Figure 1 illustrates such an average for one Au/GaN sample. Also shown is a fit to the data, using the simple phase-space model [1]. Interestingly, it was necessary to allow two different thresholds in the fit to obtain good agreement with the data. The two-threshold fit to this average yields threshold energies of 1.06 eV and 1.22 eV.

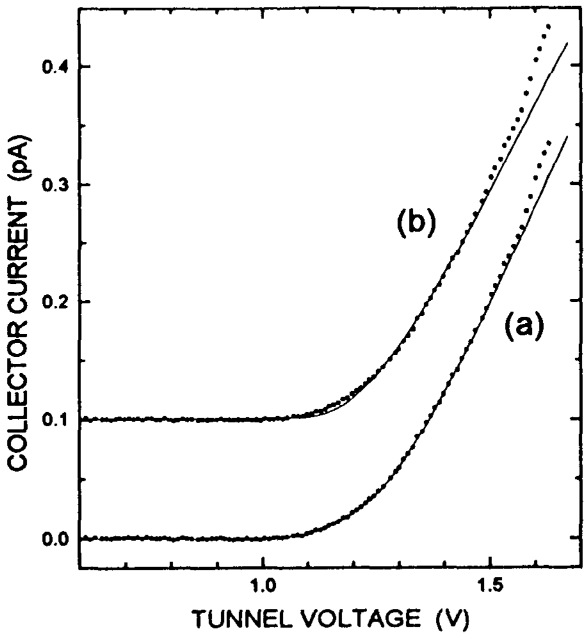

FIG. 1. BEEM I_c-V spectrum (circles) for Au(6nm)/GaN, taken at a tunnel current of 2 nA. (a) Fit (solid line) to the data using a two-threshold model, which yields thresholds of 1.06 V and 1.22 V. (b) Fit to the data assuming only one threshold, yielding a value of 1.12 V. The same data are shown in both (a) and (b), and (b) is vertically offset for clarity.

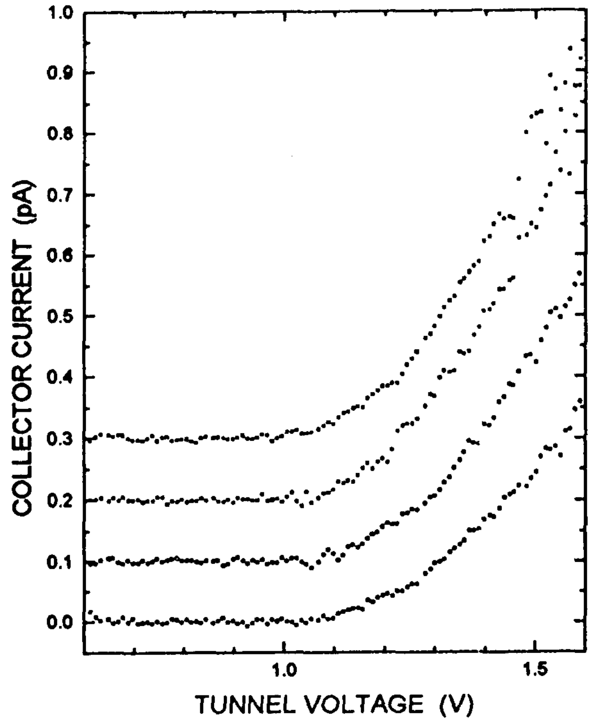

FIG. 2. Four individual I_c-V spectra taken on two different Au/GaN samples at a tunnel current of 2 nA. Although the noise level in these unaveraged spectra is high, two thresholds can usually be observed. The spectra are vertically offset for clarity.

Figure 1 also illustrates the best fit obtainable with a single-threshold model; the disagreement near threshold is pronounced, and the fit over the entire voltage range is unsatisfactory. The spectrum in Figure 1 is typical of all averages obtained for six different Au/GaN samples. The average Schottky barrier height for all data was 1.04 eV as measured by BEEM.

The ability to resolve the two thresholds is diminished by the averaging process. Although signal-to-noise is improved by averaging, any variation in the energies of the thresholds at different points on the surface will produce a smearing which decreases energy resolution. Spectrum averaging also allows the possibility of a linear combination of two single-threshold spectra, obtained at different locations, and with different threshold energies. In order to rule out this possibility, individual spectra were examined. Several examples are shown in Figure 2. Although the noise level is higher for individual spectra, it is apparent that the first spectrum threshold always occurs around 1 V, and in most cases a second threshold is apparent at approximately 1.2-1.3 V. However, the thresholds do appear to vary slightly in position, possibly due to strain or the presence of defects, implying that the signal averaging process is broadening the thresholds to some degree. Preliminary results on Pd/GaN contacts also reveal the presence of two BEEM thresholds, arguing that a metal-specific mechanism is not responsible for the second threshold.

Figure 3 presents a STM image / BEEM image pair obtained on one Au/GaN sample. Many image sets have been recorded on each sample fabricated, and all show similar behavior. Collector current is measured in nearly all areas, although the magnitude varies from about 0.2 pA to 2 pA (for a 2 nA tunnel current).

Previous BEEM results by Brazel et al. [6] on Au/GaN also displayed two thresholds; however, in that case the measured first threshold was unusually low (~0.7 V), and the second threshold was measured to be at approximately 1.04 V. It is suggestive that this second threshold agrees in energy quite well with the first threshold in the present spectra.

Interface transport in a defected area might produce a threshold lower in energy than that of the normal Schottky barrier height. Since the highest barrier heights measured by conventional I-V [7-9] are approximately equal to the 1.04 eV BEEM threshold, such defected areas would have to be very infrequent in order that they not dominate the I-V measurements. The second threshold in the prior work could then represent the Schottky barrier height energy, in agreement with the value measured in the present experiments. It is also possible, however, that defects or high strain might perturb the band structure by decreasing both thresholds in energy. In this case the two thresholds here and in the work of Brazel et al. would represent the same band minima.

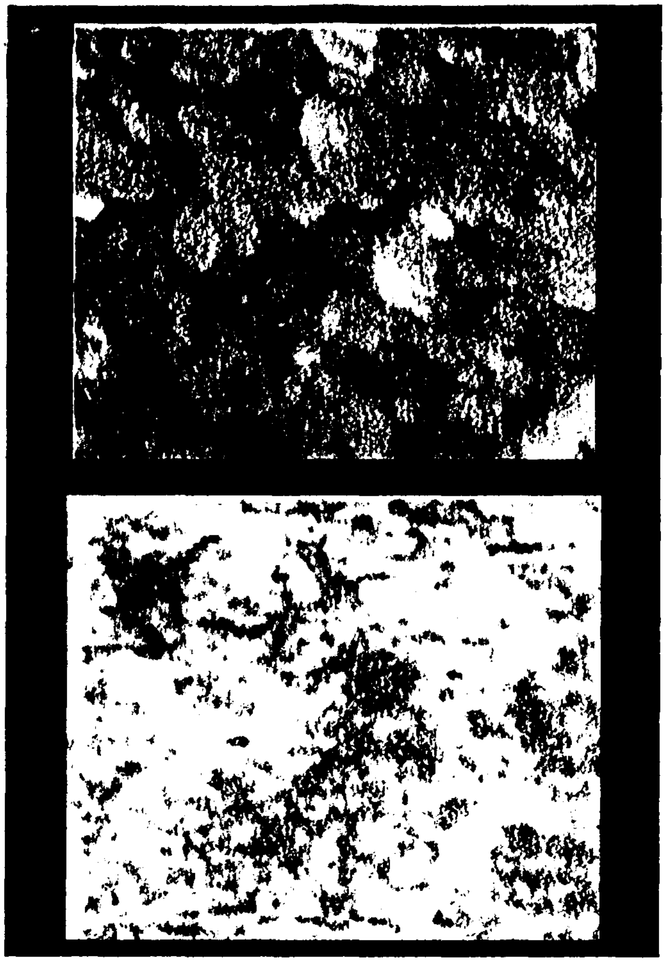

FIG. 3. STM topography / BEEM image pair for a Au/GaN sample. The topograph of the Au surface was obtained at V=0.5 V, I_t=1 nA, and the BEEM image was recorded at V=1.8 V, I_t=2 nA. I_c ranges from about 0.2 - 2 pA, and transmission is observed in most areas. Imaged area is 190 x 160 nm.

The presence of a second threshold is not expected from band structure calculations. Recent calculations [10,11] predict a second band about 2 eV above Γ_1, which is much higher than observed here. Strain effects due to the large lattice mismatch between GaN and sapphire could strongly distort the conduction bands [12] and perturb the splitting observed in BEEM spectra, and some degree of variation in strain and BEEM threshold would be expected. The variation in splitting could be investigated more quantitatively when samples exhibiting larger transmission and signal-to-noise are achieved. In addition, further work on AlGaN epilayers would determine whether a systematic change of threshold separation with Al fraction occurs. Such experiments should indicate whether the second threshold can be attributed to a higher-lying conduction band. It is interesting to note that the overshoot at V > 1.5 V of the data relative to the fit is unusual for BEEM spectra, and may indicate an additional effect of GaN band structure.

The observation of zero transmission in BEEM measurements on other GaN substrates will be investigated further in future experiments. This lack of transmission, and the extremely small BEEM currents observed in the transmitting samples, are possibly indicative of the same attenuation mechanism. This suggests that optimization of the GaN layers in some respect (most probably defect-related) might produce a further increase in transmission.

In conclusion, BEEM spectroscopy has provided a measurement of Schottky barrier height at the Au/GaN interface which agrees with the highest values from conventional electrical measurements. A second threshold is reproducibly observed in the spectra, raising the possibility of a secondary conduction-band minimum about 0.2 eV above the primary minimum. BEEM imaging reveals transmission in most areas of the interface, although the magnitude is unusually small and varies strongly. This observation, together with the lack of measurable interface transmission when using other GaN material, indicates a persistent attenuation mechanism which may be defect-related. Further work on other GaN, as well as BEEM measurements on AlGaN layers, should clarify these questions.

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1. W. J. Kaiser and L. D. Bell, *Phys. Rev. Lett.* **60**, 1406 (1988); L. D. Bell and W. J. Kaiser, *ibid.* **61**, 2368 (1988).
2. G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, *Phys. Rev. Lett.* **49**, 57 (1982).
3. L. D. Bell, M. H. Hecht, W. J. Kaiser, and L. C. Davis, *Phys. Rev. Lett.* **64**, 2679 (1990).
4. T. Meyer and H. von Känel, *Phys. Rev. Lett.* **78**, 3133 (1997).
5. L. D. Bell, W. J. Kaiser, M. H. Hecht, and L. C. Davis, In *Scanning Tunneling Microscopy*, edited by J. A. Stroscio and W. J. Kaiser (Academic Press, San Diego, 1993), pp. 307-48.
6. E. G. Brazel, M. A. Chin, V. Narayanamurti, D. Kapolnek, E. J. Tarsa, and S. P. DenBaars, *Appl. Phys. Lett.* **70**, 330 (1997).
7. M. Khan, T. Detchprohm, P. Hacke, K. Hiramatsu, and N. Sawaki, *J. Phys. D: Appl. Phys.* **28**, 1169 (1995).
8. E. V. Kalina, N. I. Kuznetsov, V. A. Dmitriev, K. G. Irvine, and C. H. Carter Jr, *J. Electron. Mater.* **25**, 831 (1996).
9. A. C. Schmitz, A. T. Ping, M. A. Khan, Q. Chen, J. W. Yang, and I. Adesida, *Semicond. Sci. Technol.* **11**, 1464 (1996).
10. W. R. L. Lambrecht, B. Segall, J. Rife, W. R. Hunter, and D. K. Wickenden, *Phys. Rev. B* **51**, 13516 (1995).
11. M. van Schilfgaarde, A. Sher, and A.-B. Chen, *J. Crystal Growth* **178**, 8 (1997).
12. Z. Yang and Z. Xu, *Phys. Rev. B* **54**, 17577 (1996).